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PERFORMANCE SPECIFICATIONS FOR STATIONARY-SOURCE MONITORING SYSTEMS FOR GASES AND VISIBLE EMISSIONS

John S. Nader, et al

National Environmental Research Center
Research Triangle Park, North Carolina

January 1974

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The purpose of this report is to provide a technical basis for the selection of stationary-source monitors that are required by Federal, State, or local regulations for emissions. The document identifies performance parameters, gives specifications and details test procedures to verify the specifications. Examples of the specifications and test procedures are provided for monitoring systems applied to gases and visible emissions. Technical data utilized for the specifications are based on the results of laboratory and field studies.

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by

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U.S. ENVIRONMENTAL PROTECTION AGENCY
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PREFACE

This report provides the background and experimental data as a technical base for the development and formulation of guidelines for monitoring pollutant emissions from stationary sources.

References to commercial products in this report directly or by inference are not to be considered in any sense as an endorsement of the product by the Government. Nor does utilization of any commercial product to generate the data reported here signify that this product necessarily meets either the performance specifications exemplified in this report or any guidelines that may be proposed on the basis of this report.

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents are the official guidelines in response to the needs stipulated in the standards of Performance of New Stationary Sources. This report does provide the technical base from which guidelines to monitors of specific pollutant emissions from selected source industries will be formulated and officially proposed in the Federal Register.

Stanley M. Greenfield, Ph.D.
Assistant Administrator
for Research and Development

CONTENTS

LIST OF FIGURES v

LIST OF TABLES vi

ACKNOWLEDGMENTS vi

INTRODUCTION 1

DEVELOPMENT BACKGROUND 5

PERFORMANCE SPECIFICATIONS 9

Parameters 9

Specifications 14

Applicability 15

SUMMARY 19

REFERENCES 21

APPENDIX A. SO_2 MONITORING CAPABILITY APPLIED TO A POWER PLANT 23

APPENDIX B. NO_x MONITORING CAPABILITY APPLIED TO A POWER PLANT 27

APPENDIX C. VISIBLE EMISSIONS MONITORING CAPABILITY APPLIED TO A POWER PLANT 29

APPENDIX D. DUKE POWER PLANT STUDY 43

APPENDIX E. EXAMPLE: PERFORMANCE SPECIFICATIONS AND SPECIFICATION TEST PROCEDURES FOR MONITORS OF POLLUTANT GAS EMISSIONS FROM STATIONARY SOURCES 49

APPENDIX F. EXAMPLE: PERFORMANCE SPECIFICATIONS AND SPECIFICATION TEST PROCEDURES FOR TRANSMISSOMETER SYSTEMS FOR CONTINUOUS MEASUREMENT OF THE OPACITY OF STACK EFFLUENTS 61

LIST OF FIGURES

Figure		Page
A-1	Flue Gas Diversion System	25
A-2	Gas Diversion and Instrument Installation Design	26
C-1	Particle Extinction Coefficients for Various Aerosols, Calculated from Mie Theory	30
C-2	Out-of-Stack Transmittance of Three Colors of Light as a Function of In-Stack Transmittance of White Light for an Experimental White (Oil) Plume	32
C-3	Out-of-Stack Transmittance of Three Colors of Light as a Function of In-Stack Transmittance of White Light for an Experimental Black (Carbon) Plume	33
C-4	Calculated Error in True Light Transmittance at 2 Degrees Detector Angle of View	34
C-5	Calculated Error in True Light Transmittance at 20 Degrees Detector Angle of View	34
C-6	In-Stack Transmittance of a Coal-Fired Power Plant Emission for Various Transmissometer Light Projection and Detection Angles	35
C-7	In-Stack Transmittance of a Coal-Fired Power Plant Emission at Various Light Projection Angles and Wavelengths	37
C-8	Out-of-Stack Transmittance of a Coal-Fired Power Plant Emission as a Function of In-Stack Transmittance	37
C-9	Transmissometer with Collimating Optics	39
C-10	Effluent Transmittance at Stack Exit as a Function of In-Stack Transmittance and Ratio of Stack Exit Diameter to Transmissometer Pathlength	41

LIST OF TABLES

Table		Page
1	Performance Specifications for Pollutant Gas Emissions from Stationary Sources.....	14
2	Performance Specifications for Transmissometer Systems for Measurement of Visible Emissions from Stationary Sources.....	15
3	Design Specifications for Transmissometer Systems for Measurement of Visible Emissions from Stationary Sources.....	15
A-1	SO_x Monitoring System Test Results.....	24
B-1	NO_x Monitoring System Test Results.....	28
D-1	SO_2 and NO_x Monitoring System Test Results.....	44

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We express our appreciation to James Homolya and Mike Barnes of the Stationary Source Emissions Measurement Staff in acknowledgment of their providing the measurement data on the Duke Power Plant Study.

PERFORMANCE SPECIFICATIONS FOR STATIONARY-SOURCE MONITORING SYSTEMS FOR GASES AND VISIBLE EMISSIONS

INTRODUCTION

The phrase continuous monitoring instrumentation conveys different meanings to various users of air pollution control equipment, depending upon the nature of the application, or the design of the system, or both. The basic concept of this type of instrumentation is, however, that the functional operation of the instrument system is automatic and more or less continuous in time. Differences in design, or application or both may be such that either the system or a component operates in a cycle having a time period ranging from fractions of a second (relatively instantaneous) to tens of minutes or more.

This report is intended to provide technical information and discussion that will assist in the formulation of federal regulations and state and local laws that require monitoring systems. The document also furnishes the instrument manufacturers and users with technical guidelines on the desired performance requirements of these systems.

In the discussion of monitoring systems for stationary-source emissions, the measurement of pollutant gases, visible effluents, and other such substances involves the whole instrument system functioning automatically and more or less continuously in time. The response time of the system that defines the specific functioning of the system with

respect to time is prescribed by the performance specifications discussed later. The monitoring systems considered include the major component operations of sampling, analysis, and data presentation. The major subsystems performing these operations are defined functionally as follows:

1. Sampling Interface. This subsystem performs one or more of the following operations: delineation, acquisition, transportation or conditioning of a sample of the source effluent or protection of the analyzer from the hostile effects of the sample or the source environment.
2. Analyzer. This subsystem (often treated as a whole and independent measurement system for analytical purposes) senses the pollutant substance or parameter and generates a signal output that is a function of the pollutant concentrations.
3. Data Presentation. This subsystem provides a display of the output signal in concentration units or other specified units.

Monitoring systems are used in engineering and research studies to evaluate performance of control equipment, in surveys of emissions for input to dispersion models, in testing for compliance with certain emission standards, and in enforcement programs. New Source Performance Standards (NSPS) proposed and promulgated by the Environmental Protection Agency (EPA) require the installation and operation of monitoring systems for specific pollutants (sulfur dioxide, nitrogen oxides, visible emissions) emitted from specified affected facilities in Category I and II sources.[1] It is anticipated that similar requirements for monitoring additional source categories (III, IV, and others)

will be proposed and promulgated in the near future. State Implementation Plans may also require monitoring of existing sources. The New Source Performance Standards propose guidelines on the selection and operation of the specified monitoring systems, and the State Implementation Plans will likely follow a similar procedure.

The performance specifications presented in this document provide technical guidelines for the application of monitoring systems to specific pollutants from selected source industries. No constraints have been placed on the sampling approach, the analytical scheme, the system design, or the development of hardware. Test procedures are presented to determine whether or not any given monitoring system can meet the prescribed performance specifications.

DEVELOPMENT BACKGROUND

Of the many possible performance parameters for continuous monitors (relating, for example, to the numerous applications and the various purposes for which data are generated), those were delineated that are essential to reliable performance and to the generation of valid data with a minimum of downtime and within a reasonable level of accuracy, compatible with the current availability of commercial systems and with the intended utilization of the data. The determining guidelines in the choice of the parameters and the development of these specifications were the need to provide data to ("flag") the operator or control officer on (1) malfunctions of control equipment, (2) verification of acceptable emission control operation, and (3) relative levels of pollutants. Since these parameters have a degree of flexibility, the values specified and test procedures prescribed can be adjusted to meet the specific needs of a given source-pollutant combination. Furthermore, other parameters may be added or some of the present ones modified or deleted to meet special needs.

Some of the parameters selected have undergone changes in definition and specification values over the period of time that the specifications have been under development and evaluation. The parameters are generally accuracy, calibration error, zero drift, calibration drift, repeatability, response time, and operational period. These are discussed more fully in the context of their definitions and the specifications given later.

In 1971, EPA supported several contract programs to evaluate commercially available monitoring systems for sulfur dioxide (SO_2)[2] and

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nitrogon oxides (NO_x)[3] in power-generating plants fired by fossil fuels. Previously, over a number of years, EPA and the former Edison Electric Institute* had conducted cooperative studies of visible emissions from power plants and the instrumental measurement of opacity.[4] These studies provided a substantial technical data base for the drafting of a set of performance specifications and test procedures to verify the specifications. (Summaries of three of these studies are given in Appendices A, B, and C, illustrating the data relating to the performance specifications; complete details are provided in the reports referenced.)

A draft of the performance specifications and test procedures for monitors of SO_2, NO_x, and visible emissions was prepared in early 1972 and circulated for review and comment within EPA and externally to a representative cross section of instrument manufacturers, industrial users, and local governmental agencies. The comments received were incorporated (where applicable) in a revised document, dated September 30, 1972.

In early 1973, at a power plant of the Duke Power Company, EPA conducted research studies to evaluate (among other objectives) the specifications and test procedures contained in the draft of September 30, 1972. (A summary of this study as it relates to the performance specifications is given in Appendix D.)

This study showed that all the performance specifications of the September 30 draft were adequate, with the exception of the accuracy specification. The range of values extended beyond the specified $\pm$ 5 percent maximum for the mean to as much as 8.3 percent.

* Currently a part of the Electric Power Research Institute.

The conclusion was to revise the specification for the accuracy to be the sum of the mean and the 95 percent confidence interval. This provided greater flexibility in the specification by prescribing the combined rather than the individual values. In addition, the September 30 draft was revised to incorporate similar changes in the specifications of the other parameters and in some of the definitions deemed more appropriate and consistent with the test procedures.

The decision to revise the specifications was based on a real and significant difference between the contract studies (TRW and Monsanto) and the in-house study (Duke plant). The former were to provide background information for the development of the specifications and test procedures. In the latter, the proposed specifications and test procedures were assessed, and their applicability to a selected source-pollutant combination was validated.

PERFORMANCE SPECIFICATIONS

The technical background discussed earlier and summarized in the Appendices makes it possible to identify parameters that adequately delineate the desired performance of a measurement system as it applies to monitoring emissions from stationary sources. This background also provides a technical basis for a set of specifications that are realistic and meaningfully consistant with the current availability of commercial stack-monitoring systems for specific pollutants from selected industries (pollutant-source combination).

PARAMETERS

The parameters that adequately delineate the desired performance of a measurement system as it applies to monitoring emissions from stationary sources are accuracy, calibration error, zero and calibration drift, repeatability, response time and operational period. Accuracy (relative) is defined as the degree of correctness with which the measurement system yields the value of gas concentration of a sample relative to the value given by a defined reference method. This accuracy is expressed in terms of error that is the difference between the paired concentration measurements. The error is expressed as a percentage of the mean value determined by the defined reference method. The absolute error is the combination of the error in the monitoring measurement and whatever error exists in the reference measurement. It is possible that the absolute accuracy of the monitor may prove to be better than that of the reference method. Theoretically, however, the assumption is made that the reference method is one tnat provides the best available accuracy. This is not always the case in practice.

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Furthermore, within a given measurement system, the error contributed by the sampling operation tends to be greater than the error from the analytical operation and becomes the limiting factor in the absolute accuracy of the measurement system as a whole. The combined effect of sampling in both the monitoring and the reference measurements can result in a significant impact on the relative accuracy.

For visible-emissions monitoring systems, relative accuracy is not specified. The reference method could be an instrument system based on first principles in its design or a set of design specifications that would implicitly involve a specified error that is predictable from theoretical considerations. To designate an instrument system as a reference method for monitoring systems that would require, in effect, the same design criteria by definition was deemed impractical and a circuitous approach. The decision was to use the design criteria for reference purposes from the beginning. The design specifications used in this document introduce a maximum error of 5 percent in opacity for particle sizes that are 10 microns in diameter. The error decreases with smaller sizes, approaching zero error at 0.3-micron sized particles.

Calibration error is defined as the difference between the pollutant concentration indicated by the measurement system and the known concentration of the test gas mixture. This type of error is measured by the use of a known concentration of the gas pollutant in some clean, dry gas stream, usually air or nitrogen. Frequently, calibration is executed by introducing the calibration test gas into the analyzer and by-passing the sampling interface. This performance specification requires that the entire measurement system be included

in the test procedure. This means introducing the calibration test gas at the sampling interface upstream of the analyzer. Thus, the sampling interface is provided the same opportunity to have an impact on calibration as on the source measurement. In the case of optical in-situ (nonextractive) systems, calibration test gas could be caused to flow through a sample cell located in the optical path. An alternative would be a cell with the calibration test gas sealed in the cell; however, the long-term stability of the calibration test gas in the sealed cell would need to be verified, possibly presenting practical problems.

Zero drift is defined as the change in measurement system output over a stated period of time of normal continuous operation when the pollutant concentration at the time of the measurements is zero. Calibration drift is defined as the change in measurement system output over a stated period of time of normal continuous operation when the pollutant concentration at the time of the measurements is the same known upscale value. Zero and calibration drift are critical parameters that have a direct effect on calibration error and ultimately on the accuracy of the data output. Both short and long term drifts are important considerations. Short-term instability can lead to misinterpretation of variations in emission concentrations; long-term instability presents a problem in interpreting long-term trends in degradation of control equipment performance. The 24-hour cycle for zero and calibration check and adjustment is stipulated to provide consistency and optimum utilization of data for evaluating day-to-day and month-to-month functioning of the source emission control facilities, or pollutant emission levels or both.

Repeatability is defined as a measure of the measurement system's ability to give the same output reading(s) upon repeated measurements of the same pollutant concentration(s). A separate specification is not given because it is implicitly covered by the confidence interval included in the calibration error.

Response time is defined as the time interval from a step change in pollutant concentration at the input to the measurement system to the time at which 95 percent of the corresponding final value is reached as displayed on the measurement system data presentation device. The response time of a measurement system is strongly influenced by the sampling approach used. Its impact on the data output is also largely related to the combination of process operation and control equipment being monitored. Generally, in a process involving relatively long term changes, such as a power plant that may require a half hour to go from half to full load, a response time of 10 minutes may be acceptable for monitoring purposes. On the other hand, in batch-type processes such as nonferrous smelters, dramatic changes in emissions occur within minutes, and a short response time is more appropriate. Extractive sampling techniques that involve several hundred feet of sampling lines obviously introduce a more significant delay in measurement response than an in-situ method in which no sample extraction is done and the response can be instantaneous.

The nature of the data output requirement and the rate of data output also play a significant role in specifying a response time. In visible-emissions (opacity) regulations on power plants, for example, an opacity of 40 percent is allowed for 2 minutes per hour. In this case, a response time less than 1 minute would be required. Slow

rates of data output such as one data point per 5 to 15 minute intervals for steady-type processes will allow some measurement systems to monitor several emission points on a "time-shared" basis. An essential point in the overall consideration of response time is that some trade-off may be required between the nature and/or rate of data output and cost. The cost impact will depend largely upon the measurement technique, the process, and the equipment utilized.

The operational period is a minimum period of time over which a measurement system is expected to operate within certain performance specifications without unscheduled maintenance, repair, or adjustment.

The location of the monitoring system on a stationary source depends largely on the purpose for which the data is being collected. For monitoring pollutant concentration so as to indicate malfunction or improper maintenance of control equipment or excessive emissions, a measurement system can be located at any point where reasonably representative sampling of the emission concentration can be made. General guidelines include (1) consideration of convenience and accessability for maintenance of the monitoring system, and (2) location downstream of any pollution control equipment and upstream of a dilution or other process affecting the emission concentration. It may be necessary to conduct preliminary measurements traversing the stack diameter to determine the nature of the concentration profile and to establish a representative sampling location for the final installation of the monitoring system.

Stack monitoring systems that utilize different sampling approaches are commercially available; they include extractive, in-situ, and remote techniques.[5] The performance specifications provide no constraints

on the sampling interface or any other major subsystem (see Introduction) within the monitoring system. Many source monitors that require extractive sampling are available as analyzers exclusive of the "interface" subsystem. Much information is available on the performance of the analyzer in the laboratory under controlled conditions and on field applications. The sampling interface has a significant impact on performance reliability and is specifically related to each analyzer-source combination. Data on the various combinations, including the interface as a total system, are very limited or nonexistent.

SPECIFICATIONS

The performance parameters for gas-pollutants and visible emissions that have been defined are assigned values as shown in Tables 1 and 2, respectively. Table 3 shows design specifications that are technically discussed in Appendix C.

Table 1. PERFORMANCE SPECIFICATIONS FOR POLLUTANT GAS EMISSIONS FROM STATIONARY SOURCES

Parameter	Specification
Accuracy (relative)	≤20% of mean reference value[a]
Calibration error	≤ 5% of each test gas value[a]
Zero drift (2 hr)	≤ 2% of emission standard[a]
Zero drift (24 hr)	≤ 4% of emission standard[a]
Calibration drift (2 hr)	≤ 2% of emission standard[a]
Calibration drift (24 hr)	≤ 5% of emission standard[a]
Response time	≤ 10 min
Operational period	168 hr

[a]Absolute mean value ± 95 percent confidence interval.

Table 2. PERFORMANCE SPECIFICATIONS FOR TRANSMISSOMETER SYSTEMS FOR MEASUREMENT OF VISIBLE EMISSIONS FROM STATIONARY SOURCES

Parameter	Specification
Calibration error	≤10% of test filter value[a]
Zero drift (24 hr)	≤10% of emission standard[a]
Calibration drift (24 hr)	≤10% of emission standard[a]
Response time	≤ 10 sec
Operational period	168 hr

[a]Absolute mean value ± 95 percent confidence interval.

Table 3. DESIGN SPECIFICATIONS FOR TRANSMISSOMETER SYSTEMS FOR MEASUREMENT OF VISIBLE EMISSIONS FROM STATIONARY SOURCES

Parameter	Specification
Spectral response[a]	Peak and mean response within 500 to 600 nm; less than 10 % of peak response outside of 400 to 700 nm.
Angle of view[b]	5 degrees maximum (total angle)
Angle of projection[c]	5 degrees maximum (total angle)

[a]The relative response of a transmissometer to radiation of different wavelengths.

[b]The maximum (total) angle of radiation that is seen by the photo-detector assembly of an optical transmissometer.

[c]The maximum (total) angle of radiation that is projected by the lamp assembly of an optical transmissometer.

APPLICABILITY

The performance parameters and their specified values in Tables 1 and 2 must be considered in the context of their application before

they can be utilized with any real meaning. Furthermore, test procedures* must be established to verify that a monitoring system does indeed meet the specifications. The test procedures must be considered not only in the context of the measurement system's application but also, just as importantly, in relation to how the data generated by the system is to be used. In fact, the anticipated utilization of the data is implicit in the development of the specification values cited in Tables 1, 2, and 3. As stated earlier, the guideline used in the development of these performance specifications has been largely a middle-of-the-road approach that would permit optimum utilization of commercially available monitoring systems; that is, systems that will have the potential to meet many needs adequately.

Appendices E and F are examples of how the specifications in Tables 1, 2, and 3 may be applied in conjunction with test procedures as guidelines in the assessment or selection of monitoring systems for pollutant gas emissions and visible emissions, respectively. It is necessary to use the regulatory language in the examples given to maintain the integrity of the values and definitions of the parameters and the test procedures for the sake of internal consistency because of the interaction among these factors.

The guidelines in Appendices E and F are potentially applicable to the following needs:

1. Criteria that provide consistent and valid data relevant to measurement needs and ensure the generation of data of known quality, compatible with specified use.

*Specified in Appendices E and F.

2. Criteria that provide clearly defined objectives for instrument development and manufacture.

3. Performance parameters that permit maximum flexibility in design and fabrication of the system hardware, including electronic equipment, for minimum cost and with minimum complexity.

4. Criteria for the user to assess available systems on a common basis and to make appropriate selection for various applications that may include monitoring process operation, control operation, and emission levels.

It is possible to move toward tighter or looser specifications than those given in the examples shown. Whether or not it is necessary or desirable to do so depends upon the specific pollutant-industry combination, the intended utilization of the data, and other factors, such as economic considerations and experience. The constraints on moving toward tighter specifications are not the lack of present technological capability but rather the cost impact, current availability of commercial systems, and practical experience with a given pollutant-industry combination. Technical data on the applicability of specifications to various pollutant-industry combinations are gradually being developed.

The guidelines in the appendices are supported technically by actual application to the pollutant-industry combinations for SO_2, NO_x, and visible emissions in coal-fired power plants based on the development background. This experience enables an understanding of the applicability of the guidelines. It provides the proper basis for considering any changes in the specification values and/or test procedures as may be

dictated by special needs in the utilization of the data for these same pollutant-industry combinations. The parameters delineated should apply in general. The specification values and test procedures exemplified possibly can be made generally applicable to other pollutant-industry combinations. Any projected application to other combinations is more or less valid, depending on the intended or end usage of the data generated and on whether or not the applicability of the guidelines to the new combinations has been demonstrated.

SUMMARY

Parameters for evaluation of the performance of continuous monitors for the measurement of emissions from stationary sources have been delineated and defined. Field testing programs have been conducted to provide technical background on the availability and applicability of commercially available source monitoring instrumentation. The technical data generated by these field studies are shown as the basis for the development of performance specifications and of test procedures by which these specifications can be verified.

Examples are given of how performance specifications may be applied in conjunction with test procedures as guidelines in the assessment or selection of monitoring systems for pollutant gas emissions and visible emissions from stationary sources. Applicability of these guidelines was discussed within the constraints of specified pollutant-industry combinations and utilizations of the data generated.

REFERENCES

1. Standards of Performance for New Stationary Sources, Federal Register, Vol. 36, No. 247, December 23, 1971; Vol. 38, No. 111, June 11, 1973; Vol. 38, No. 84, May 2, 1973.

2. Jaye, F. C. Monitoring Instrumentation for the Measurement of Sulfur Dioxide in Stationary Source Emissions. TRW Contract No. EHSD 71-73. NTIS PB 220-202. Office of Research and Monitoring, U. S. Environmental Protection Agency, February 1973. 124 p.

3. Snyder, A. D. et al. Instrumentation for the Determination of Nitrogen Oxides Content of Stationary Source Emissions. Vol. I and Vol. II. Monsanto Contract No. EHSD 71-30. NTIS PB 204-877 and NTIS PB 209-190. EPA. January 1972.

4. Conner, W. D. and J. R. Hodkinson. Optical Properties and Visual Effects of Smoke-Stack Plumes. EPA, Research Triangle Park, N. C. Publication Number AP-30. May 1972. 89 p.

5. Nader, J. S. Developments in Sampling and Analysis Instrumentation for Stationary Sources. J. Air Pollut. Contr. Assoc. 23: 589-591, July 1973.

6. Hodkinson, J. R. The Optical Measurement of Aerosols. In: Aerosol Science, Davies, C. N. (ed.). New York, Academic Press, 1966. p. 289.

7. Ensor, D. S. and M. J. Pilat. The Effect of Particle Size Distribution on Light Transmittance Measurement. Amer. Ind. Hyg. Assoc. J. 32: 287-292, May 1971.

8. Peterson, C. M. and M. Tomaides, In-Stack Transmittance Techniques for Measuring Opacities of Particulate Emissions from Stationary Sources. Environmental Research Corporation. Contract No. 68-02-0509. NTIS PB 212-741. EPA. Research Triangle Park, N. C. April 1972. 87 p.

9. Homolya, J. B. A Review of Available Techniques for Coupling Continuous Gaseous Pollution Monitors to Source Emissions. EPA. (Presented at 165th National American Chemical Society Meeting. Dallas, Texas. April 8-13, 1973. 12 p.)

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APPENDIX A. SO_2 MONITORING CAPABILITY APPLIED TO A POWER PLANT[2]

In September 1970, the Environmental Protection Agency contracted with TRW Systems Group, Redondo Beach, California, to perform the required field tests to evaluate commercially available instrumentation for monitoring SO_2 emissions from a coal-burning power plant. This program included an identification of commercially available instrumentation, selection of instrumentation for the field test, design of the field test, and operation of the field test site.

TRW surveyed the instrument marketplace to identify manufacturers, vendors, and developers of SO_2 measurement instrumentation. Eighteen manufacturers and/or vendors responded, and 17 companies indicated an active program in the development of SO_2 measurement units. The survey revealed that, as of January 1, 1971, 12 SO_2 source monitors were commercially available. The detection and analysis scheme consisted of one of the five following principles: spectroscopic, electrochemical, conductometric, coulometric, and mass spectrometric. The spectroscopic technique included UV/visible absorption, nondispersive and dispersive IR/visible absorption. After this information was received, additional companies announced the sale of new instruments, which operated on one of the five principles mentioned above, except that one used flame stimulated emission spectroscopy (flame photometric).

The contractor initiated the field test study with six SO_2 monitors that were available for delivery in accordance with the required schedule. They utilized the first four of the five analytical principles given above.

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The field tests were conducted at a coal-fired steam generating plant. The unit employed in the SO_2 monitor test burned coal with approximately 0.5 percent sulfur that produced an effluent SO_2 level of approximately 250-300 ppm. The results are summarized in Table A-1 for the test set up shown in Figures A-1 and A-2.

Table A-1. SO_2 MONITORING SYSTEM TEST RESULTS[a]

Test parameter	Value range
Accuracy[b]	-4.0 % ± 14% to 0.5% ± 6.3%
Calibration error[c]	0.3% ± 0.05% to 2.9% ± 3%
Zero drift (2 hr)	0.1% to 3%
Zero drift (24 hr)	-2.2% ± 0.1% to 3.2 ± 3%
Calibration drift (24 hr)	-0.4% ± 0.5 to 1.1% ± 2.1%
Repeatability	-6.1% to 0.6%

[a] All values are reported as mean values ± 95 percent confidence intervals as percentage of 1000 ppm span.

[b] Accuracy expressed as mean deviation ± 95 percent confidence interval of instrument readings versus barium-thorin titration Method 6, Federal Register, December 23, 1971.

[c] Error expressed as mean difference ± 95 percent confidence interval between least squares calibration curves (5 points) and single point (1080 ppm) span calibration when measured with three other calibration gases at 190, 660, and 880 ppm.

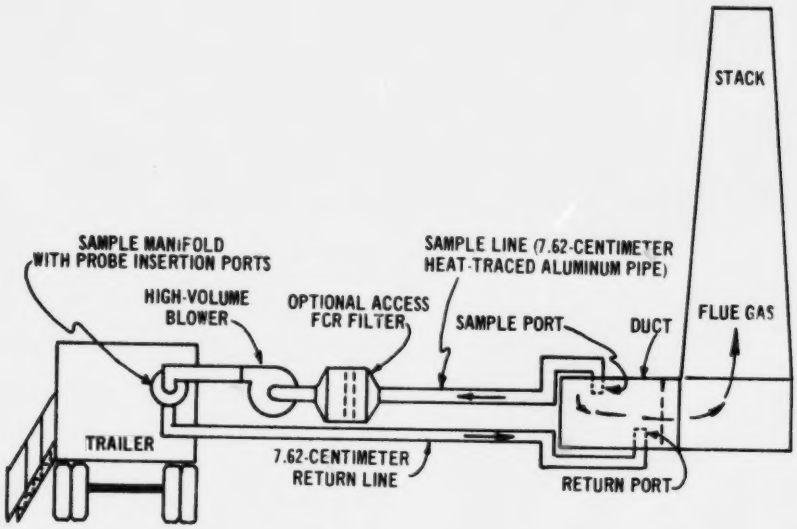

Figure A-1. Flue gas diversion system.

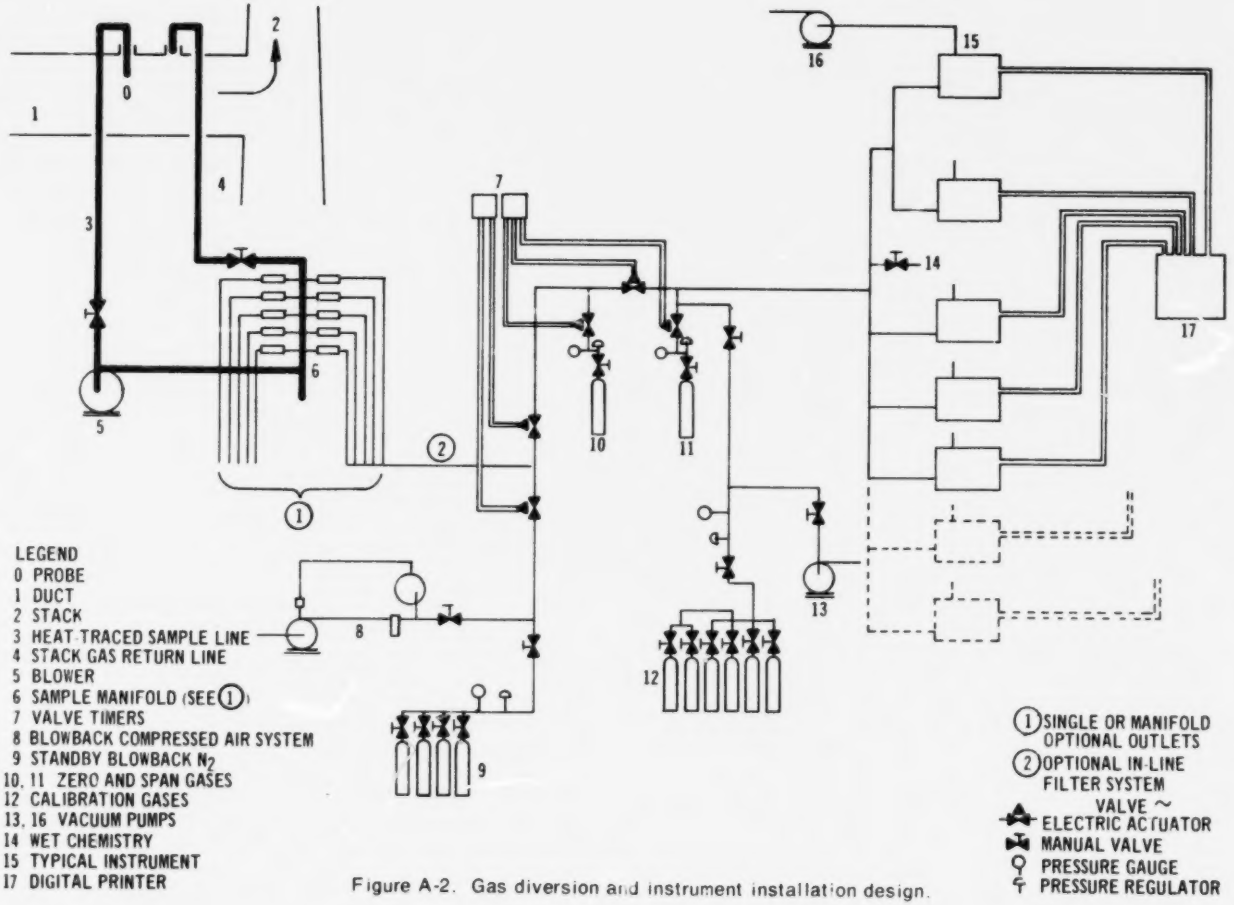

Figure A-2. Gas diversion and instrument installation design.

APPENDIX B. NO_x MONITORING CAPABILITY APPLIED TO A POWER PLANT

In December 1970, the Environmental Protection Agency contracted with Monsanto Research Corporation, Dayton, Ohio, to perform the required field tests to evaluate commercially available instrumentation for monitoring NO_x emissions from a coal-burning power plant. This program included (1) identification of the manufacturers and users of NO_x-monitoring equipment to determine the state-of-the-art, (2) performance of laboratory tests of suitable monitoring equipment, and (3) performance of field testing at a coal-fired power plant. This approach was taken (as opposed to the approach for SO_2 monitoring) because, at the time of program inception, it was determined that NO_x monitoring was ill-defined and in a less advanced state than SO_2 monitoring.

Monsanto obtained information from 85 organizations regarding the manufacture or use of NO_x monitoring instrumentation. As of January 15, 1971, nine NO_x source monitors were commercially available. The detection and analysis scheme consisted of one of the following principles: spectroscopic, electrochemical, and mass spectrometric. As in the case of SO_2, the spectroscopic technique included UR/visible absorption, nondispersive and dispersive UV/IR visible absorption. In the study, Monsanto used seven NO_x monitors, which utilized the first two of the three analytical principles mentioned above.

The NO_x monitor study included both laboratory and field test programs at a coal-fired steam generating plant. The tests at this source showed SO_2 levels of 1800-2400 ppm SO_2 and NO_x levels of

250-350 ppm, of which about 10 ppm were NO_2. Table B-1 summarizes the performance of several monitors in the laboratory and field tests.

Table B-1. NO_x MONITORING SYSTEM TEST RESULTS[a]

Test parameters	Value range
Accuracy[b]	-2.3% ± 4.5% to -7.4% ± 4.3%
Calibration error[c]	-10% ± 0.4% to 9.4% ±5%
Zero drift (2 hr)	0.2% ± 1.1% to -1.5% ±4.4%
Zero drift (24 hr)	0.4% ± 0.5% to 0.6% ± 7.1%
Calibration drift (24 hr)	-6.6% ± 4.3% to 3.7% ±8.2%
Repeatability	<2%
Response time	10 min

[a] All values reported as mean values as percentage of 500 ppm span.

[b] Accuracy expressed as mean deviation ± 95% confidence interval of instrument readings versus phenol disulfonic acid analysis Method 7, Federal Register, August 17, 1971. (Field test.)

[c] Error expressed as mean deviation ± 95 percent confidence interval of instrument readings versus standard calibration gas.

APPENDIX C. VISIBLE EMISSIONS MONITORING CAPABILITY APPLIED TO A POWER PLANT

Visible emissions are measured in terms of the amount of light attenuated or transmitted by the emissions in the visible portion of the spectrum relative to the incident light. The percentage of light attenuated is defined as the opacity of the emissions. The light transmitted is the transmittance of the emissions. The sum of the transmitted light and the attenuated light constitutes the total incident light. Therefore, a plume that does not attenuate any incident light is invisible and will have a transmittance of 100 percent and an opacity of 0. A plume that attenuates all the incident light is said to be 100 percent opaque; it will have an opacity of 100 percent and a transmittance of 0. An instrument that measures and monitors opacity or transmittance is referred to as a transmissometer. Instruments that monitor transmittance of an effluent within the stack are available commercially as in-stack transmissometers. As many as 23 manufacturers have been identified as producers of in-stack monitors, and more are appearing on the scene.

Two important optical characteristics of transmissometers must be specified to obtain similar performance from instruments: the operating wavelength and light collimation of the instruments. The operating wavelength is important because fine particulates attenuate shorter wavelength radiation more than longer wavelengths. Proper

selection of the operating wavelength of the transmissometer will also minimize interference due to absorption and radiation from gases and water vapor in the emissions. The light collimation is important because measurement of the true transmittance and opacity of aerosols requires the exclusion of light scattered by the aerosols from the measurement. Collimation requires an optical design that limits the light viewing and projection angles of the transmissometer. No restriction on viewing and projection angles results in instruments with poor sensitivity and performance.

The effect of wavelength and particle size on the transmittance of smoke can be illustrated by examining the theoretical particle extinction efficiency curves reported by Hodkinson[6] (Figure C-1).

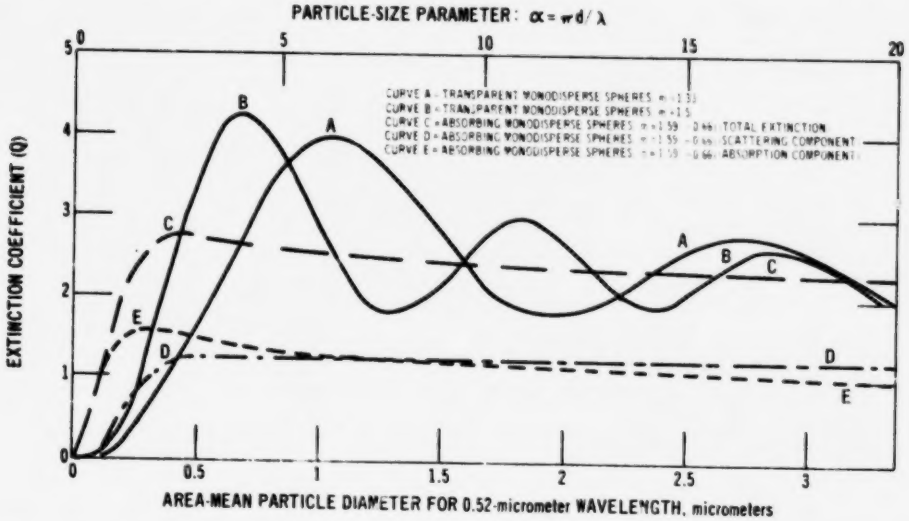

Figure C-1. Particle extinction coefficients for various aerosols, calculated from Mie theory.

The particle extinction efficiency factor Q depends on the particle refractive index relative to the surrounding medium, its shape, and its size relative to the wavelength, usually expressed as $\alpha = \pi d/\lambda$, where d is the particle diameter and λ is the wavelength of light.

Particles that are much smaller than the illuminating wavelength ($\alpha = 0.3$, d = 0.05 microns in visible light) contribute little to the opacity of particulate emissions since their extinction efficiency seldom exceeds 10^{-2}. As the particle size increases, however, their extinction efficiencies increase rapidly. As the particle size of a transparent sphere increases above $\alpha = 0.3$, its extinction coefficient attains a maximum value of about 3 or 4 when α is between 4 and 6 (d = 2/3 and 1 micron in 0.5 micron light) and settles after some oscillation to the limiting value 2 (Figure C-1, curves A and B). If the particle is transparent but irregular in shape, the particle extinction coefficient obtains the value of 2 around $\alpha = 4$ with little or no oscillation. If the particle is absorbing, the particle extinction curve rises to 2 without oscillation with little or no maximum when $\alpha = 2$ to 3 (d = 0.3 to 0.5 micron in 0.5 micron light) (Figure C-1, curve C).

In practice, the extinction coefficient of the aerosol in smokestacks will not exhibit the extreme oscillatory behavior of the individual particle extinction coefficient but will be smoothed out because of the normal polydisperse nature of the aerosol. Smoothing of the particle extinction curve also results when the effective spectral response of the transmissometer is polychromatic. Consequently, the opacity of an aerosol with particle size parameter greater than 6 (mean diameter of about 1 micron in 0.5 micron light) will not generally be a function of transmissometer wavelength; and, if the aerosol is highly absorbing, the opacity can be independent

of wavelength when the particle size parameter exceeds 3 (mean diameter of about 0.5 micron in 0.5 micron light). At smaller particle sizes, the opacity is wavelength dependent since the volume extinction coefficient is proportional to λ^{-n}, $0 < n < 4$. The effect of wavelength on the transmittance of fine particulates is illustrated by Conner and Hodkinson[4] for experimental white (oil) and black (carbon) plumes (Figures C-2 and C-3).

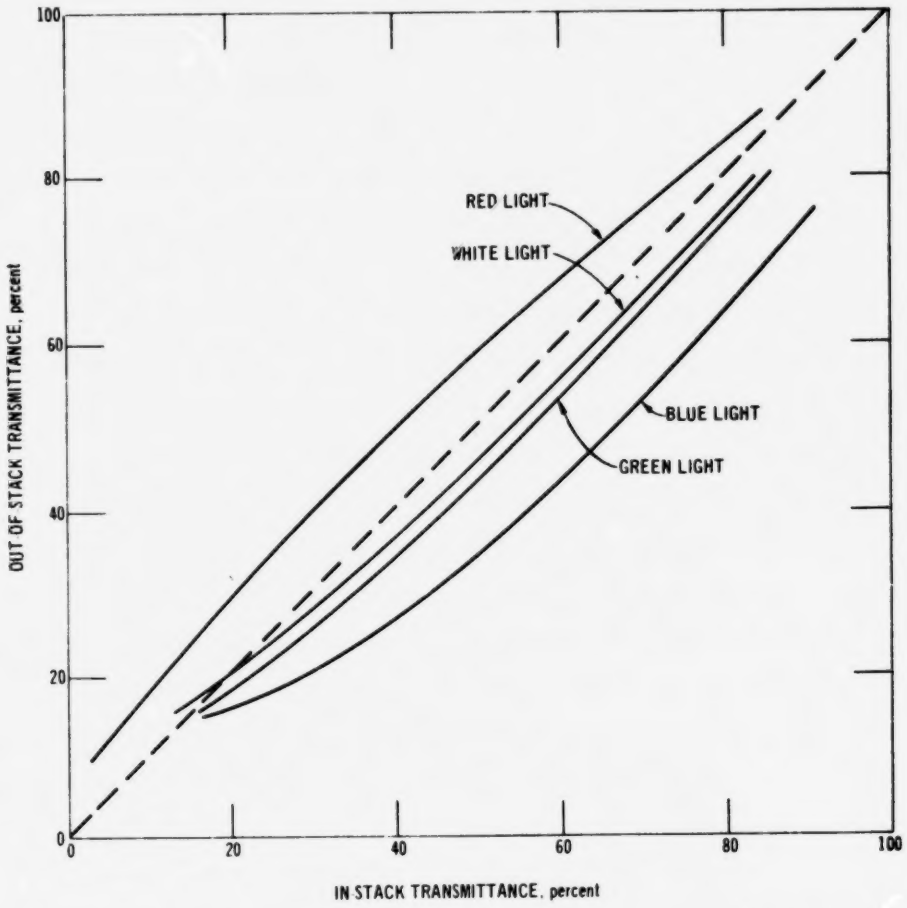

Figure C-2. Out-of-stack transmittance of three colors of light as a function of in-stack transmittance of white light for an experimental white (oil) plume.

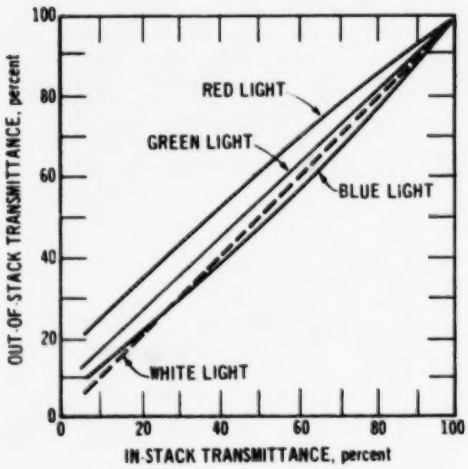

Figure C-3. Out-of-stack transmittance of three colors of light as a function of in-stack transmittance of white light for an experimental black (carbon) plume.

The effect of the detector angle of view can be illustrated by use of the theoretical results reported by Ensor and Pilat. [7] These results were used to calculate the error in the true light transmittance as a function of the true light transmittance at various particle size distributions for detector angles of 2^{o} and 20^{o} (Figures C-4 and C-5). The error E_t in the true light transmittance is defined as:

$$E_t = \frac{(T_{measured} - T_{true})}{T_{true}} \times 100$$

Figure C-6 shows that for a 2-degree detector angle of view the error in the true transmittance is in general less than 5 percent in the 40 to 100 percent transmittance range for an aerosol with particles of size geometric standard deviation 3 and particle mass mean diameter less than 10 microns. Figure C-5 shows that for a

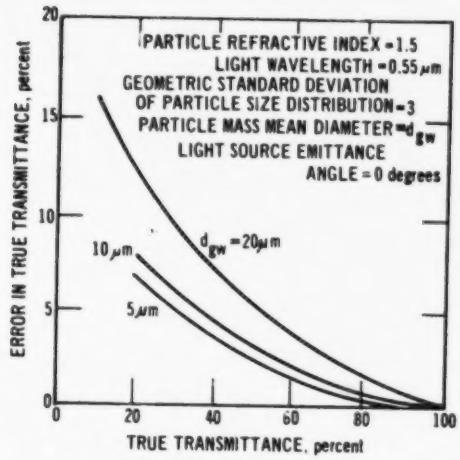

Figure C-4. Calculated error in true light transmittance at 2 degrees detector angle of view.

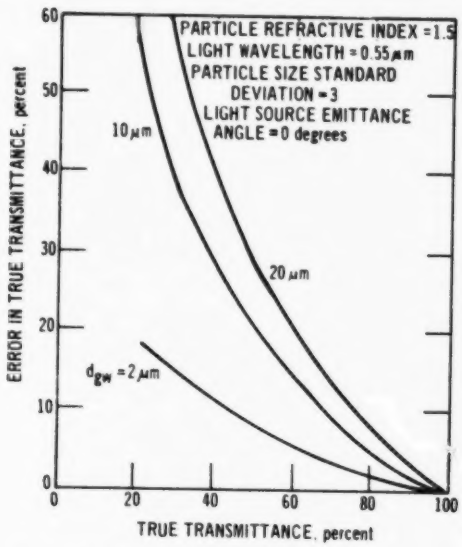

Figure C-5. Calculated error in true light transmittance at 20 degrees detector angle of view.

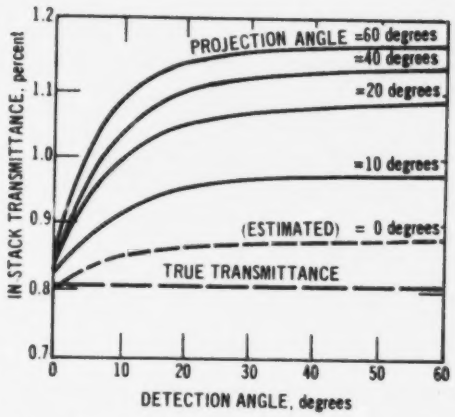

Figure C-6. In-stack transmittance of a coal-fired power plant emission for various transmissometer light projection and detection angles.

20-degree detector angle of view, the error in true transmittance can range up to 30 percent in the 40 to 100 percent transmittance range for the same aerosol. In general, the error associated with a given detector viewing angle increases with increased particle mean diameter, and, at a given particle mean diameter, decreases with increasing particle size geometric standard deviation (increasing polydispersity of the particle size).

An experimental study of the effect of the collimating angles of the detector and light source of a transmissometer on the measurement of the opacity of emissions from a coal-fired steam generator was conducted by Peterson and Tomaides.[8] They also examined the opacity of this emission at several wavelengths within the visible light region and considered the correlation between the in-stack opacity measurement and the opacity of the plume.

To conduct the study, the investigators developed an experimental transmissometer with variable detector and lamp collimating angles

and with provision for inserting interference filters. The transmissometer was installed alongside a reference transmissometer in the stack of a coal-fired electric power generating plant. The reference transmissometer was well collimated and had a photopic spectral response.

The stack was of cylindrical steel construction, approximately 3 meters in diameter. The top of the stack was 89 meters above ground level and 55.5 meters above the boiler room roof, through which it protruded. The stack carried the effluent from a 120- megawatt boiler, equipped with electrostatic precipitators rated at 13 percent efficient. The experimental and reference transmissometers were located in the stack 15.2 and 18.9 meters above the roof, respectively. The opacity of the emission was controlled during the study by varying the precipitator voltage.

The collimating angle tests (Figure C-6) show that the size of the collimating angles of the detector and light source produce similar errors and both must be constructed as small as practical to minimize the error in the measured transmittance and opacity. The transmittance measurements at four different wavelengths within the visible spectrum showed that the transmittance of the emission increased with each decrease in wavelength (Figure C-7). This result indicates that the particle size was large enough to place the particle extinction coefficient beyond the first maxima of the extinction efficiency curve. The in-stack and plume opacity measurements showed good correlation (Figure C-8). The in-stack measurements were with the reference transmissometer, which had a 3-degree angle of view and near 0-degree light projection

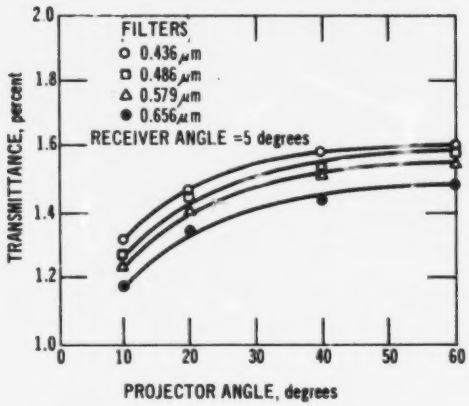

Figure C-7. In-stack transmittance of coal-fired power plant emission at various light projection angles and wavelengths.

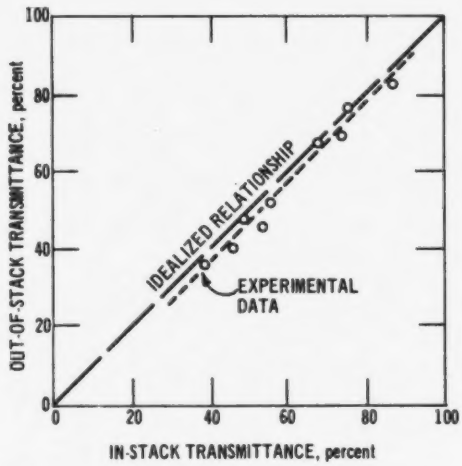

Figure C-8. Out-of-stack transmittance of coal-fired power plant emission as a function of in-stack transmittance.

angle. The out-of-stack plume transmittance measurements were made with a narrow 1/2 degree angle telephotometer by the method of contrasting targets described by Conner and Hodkinson.[4]

Clearly, the wavelength response of the transmissometer used for compliance to opacity regulations must measure the opacity of the emissions to visible radiation since the regulation is based on the visibility of the emissions. This is best accomplished by restricting the spectral response of the transmissometer to the visible. Interferences caused by the absorption and emission of radiation by hot gases are also at a minimum in this region of the spectrum. This specification can be met by proper selection of detector and lamp or detector-lamp-filter combination. Most commercial instruments can easily meet this specification.

In theory, the collimation angles for the light source (projection angle) and for the detector (detection angle) should be 0 to avoid the detection of scattered light. This is an ideal that cannot be met in practice because the execution of any instrument design will require a finite collimation angle. Associated with the finite collimation angle is a systematic error in the transmission that is a function of the particle size and particle size distribution in the particulate emission. There are limiting factors on how small a collimation angle one can can specify. As one approaches smaller collimation angles, instrument cost increases and stability and optical alignment problems are generated. In practice, a compromise is necessary in which a moderate restriction on the collimating angles for the detector and light source is specified. Accordingly, an angle of 5 degrees

(total angle) or less is recommended. Empirical data on the emissions of a coal-fired steam generator[8] indicate that a transmissometer with 5-degree collimating angles measure the opacity about 5 percent low relative to the true value (Figure C-6). This error would approach 0 for the same transmissometer applied to a source with a particle size distribution shifted to smaller mass mean diameters (towards submicron sizes, Figures C-4 and C-5).

The 5-degree (maximum) specification reportedly can be met with little or no impact on cost. It is a good compromise between large errors introduced at larger angles and alignment and instability problems introduced at smaller angles.

Most commercial transmissometers do not meet this collimation specification; however, they can meet the specification by simply adding light baffling or by adding collimating lenses and apertures to their detector and light source. A collimated transmissometer is shown in Figure C-9.

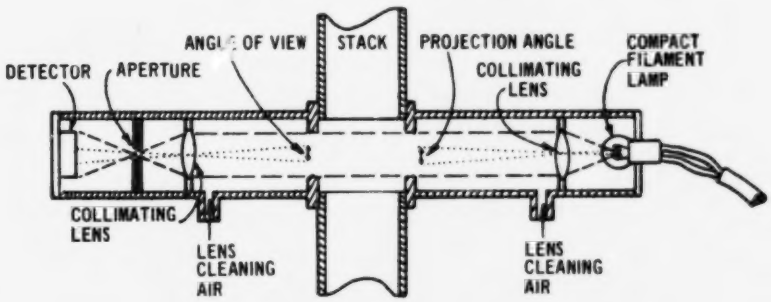

Figure C-9. Transmissometer with collimating optics.

The design specifications discussed above are important for performance stability and accuracy, and they represent minimal requirements to obtain equivalent performance of different transmissometers for measurement of the opacity of stationary source emissions. Most commercial transmissometers need improvement and testing to demonstrate acceptability. The once-a-day minimum calibration requirement is particularly difficult for most instruments since they do not generally have in-stack calibration capability.

Since opacity is dependent upon the depth of effluent (pathlength) through which the measurement is made, the in-stack pathlength for the measurement and the pathlength for the applicable opacity regulation and instrument readout must be specified. It is recommended that the pathlength for the measurement include the entire width of the stack or duct. An installation that uses a pathlength less than the effluent depth would negate the averaging advantages of across the stack in-situ measurements. Since the opacity regulation is based on the opacity of the plume emitted by the source, an in-stack measurement of opacity at a pathlength different from the diameter of the plume at the stack exit must be corrected to the opacity of the effluent for a pathlength equal to the stack exit diameter to determine compliance with the regulation. The relation for the correction is:

$$\log(1-O_1) = (l_1/l_2) \log(1-O_2)$$

where l_1 is the stack exit diameter and O_1 is the opacity of the effluent at the stack exit diameter, l_2 is the in-stack pathlength of the transmissometer and O_2 is the measured opacity of the effluent within the transmissometer path. This relation is shown in Figure C-10

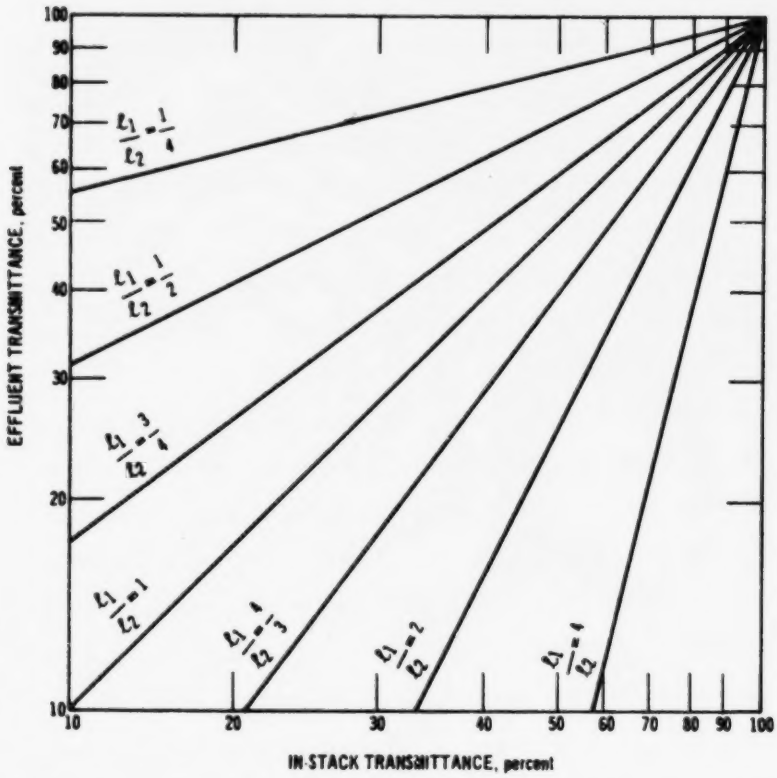

Figure C-10. Effluent transmittance at stack exit as a function of in-stack transmittance and ratio of stack exit diameter to transmissometer pathlength.

in terms of transmittance (transmittance equals 1 minus opacity).

The transmissometer output should permit expanded display of the in-stack opacity on a standard 0 to 100 percent readout scale. A graph or custom-made scale should be provided with each installation to show the relation between the standard 0 to 100 percent readout scale and the opacity of the effluent for a pathlength equal to the stack exit diameter. The full-scale measurement should represent an opacity approximately 1.5 times the maximum allowable opacity of 40 percent for steam generators.

Caution must be used in the location of the transmissometer. The instrument should be located so that a representative particulate concentration passes through the viewing volume. For devices using slotted alignment tubes, care should be taken to ensure that the design does not interfere with free flow of the effluent through the entire optical volume. If the transmissometer must be located near a bend or obstruction where a representative particulate concentration is in doubt, the location should be determined experimentally.

Good operational stability requires maintenance of optical alignment and clean optical surfaces. Installation and design requirements are directed toward minimizing the effects of temperature, vibration, and other operational conditions that can cause optical misalignment and lead to excessive drift. Installation requirements will depend largely on the characteristics of the plant operation and this factor can vary significantly among various industries. Accordingly, installation costs can vary depending upon the severity of installation conditions. The adequacy of the system's lens cleaning mechanism must also be judged in the context of the specific installation. It is advisable to observe closely the performance of a system for a period of time following installation and to take steps, if necessary, to correct any deficiencies that may develop.

Automatic lens cleaning and calibration and installation will have an impact on cost. An alternative to automatic cleaning and calibration is manual maintenance. Aside from relative cost considerations, it is necessary to consider the reliability of manual maintenance versus automatic operation. Experience to date is inadequate to assess the trade-off possibilities and the impact on cost.

APPENDIX D. DUKE POWER PLANT STUDY

EPA conducted a source measurements study over a 3-month period (January thru March of 1973) at a pulverized-coal fired power plant of the Duke Power Company in Charlotte, North Carolina.[9] The study had as one of its prime objectives the comparison of various sampling approaches for the measurement of SO_2 by source emission monitors and the stability of operation of an opacity monitoring system. The three different approaches to gas measurement included: across-the-stack and within-the-stack (in-situ) measurement with UV absorption; extractive sampling with UV absorption analysis; and remote sensing with UV correlation spectroscopy. All these measurements were compared to the compliance test method (Method No. 6 of the NSPS). An additional objective was to evaluate and validate the applicability of the proposed specifications and test procedures for monitoring SO_2 and visible emissions on a coal-burning power plant.

Commercially available instrument systems that represented the three measurement approaches to SO_2 monitoring were installed on the stack of a 150-megawatt wall-fired boiler. The stack was also instrumented with an across-the-stack transmissometer (opacity monitor) for measurement of visible emissions and with instrumentation to monitor continuously stack gas velocity. The control equipment consisted of both hot and cold electrostatic precipitators containing a total of 14 stages. This instrumentation permitted control of the particulate loading in the stack emissions over a range in finite increments determined by cutting off a specific number of precipitator stages. A small building erected at the base of the stack housed the instrument control units and the digital data acquisition equipment.

The instrument systems were operated continuously after installation for a 90-day period. During this period, the proposed (September 30, 1972, draft) performance specifications test procedures were executed as prescribed and were evaluated on their applicability. The instrumentation was also left unattended for about 60 days for a more extensive reliability test. Within the total period, 65 measurements by NSPS Method No. 6 were made as reference measurements for correlation with the corresponding (in time) instrumental measurements. Measurement data were also obtained at three levels of particulate loading ranging from 2 percent to 47 percent opacity, effected by appropriate cutback on various stages of precipitator control. Table D-1 summarizes some of the results on the performance tests on the SO_2 monitoring systems.

Table D-1. SO_2 AND NO_x MONITORING SYSTEM TEST RESULTS

Test parameter	Results, %	
	SO_2	NO_x
Accuracy[a]	3.8 to 32	15 to 35
Zero drift (2 hr)[b]	0.32 to 1.8	0.08 to 1.5
Zero drift (24 hr)[b]	1.0 to 4.5	0.21 to 3.3
Calibration drift (2 hr)[b]	0.82	1.3 to 6.6
Calibration drift (24 hr)[b]	3.6 to 4.8	1.7 to 5.0

[a]Result is the sum of the absolute mean error and the 95% confidence interval as a percentage of the mean measurement by Method 6 for SO_2 and by Method 7 for NO_x. Method 7 for NO_x was run in sets of two. Sets of three should improve the confidence interval and the accuracy.

[b]Result is the sum of the absolute mean value and the 95% confidence interval as a percentage of the emission standard (620 ppm for SO_2 and 525 ppm for NO_x).

The study indicated that the specifications and test procedures were applicable and valid, except that the accuracy specifications may need to be modified if maximum possible utilization is to be made of available monitoring systems. The rationale for such a consideration is that this test was specifically for a selected pollutant-source combination involving a representative cross section of measurement approaches. This study was the first real assessment of the applicability of the proposed specifications and test procedures. Nonetheless, such a consideration would be predicated on the purpose for monitoring, the required accuracy, and the intended utilization of the data.

The evaluation of the specifications and test procedures for opacity indicated that they were applicable and valid. Most of the effort on the opacity evaluation was directed at the zero and calibration drift parameters as a measure of the system's stability. As long as the system was in proper functioning condition, it maintained zero and calibration stability that was significantly more than adequate. Zero and calibration drift were less than 0.5 percent and 0.3 percent opacity per week, respectively. The instrument was unattended and checked out on a weekly basis during the 90-day period. At each check the following actions were taken: the alignment of the system was verified; all optical surfaces exposed to the emissions were cleaned; and the filters of the air purge system (to keep the optics clean) were checked and cleaned as required.

The zero drift and calibration drift were not accumulative. No optical alignment drift was noted over the 3-month period. Cleaning

of the optical surfaces showed no measurable effect on the zero and calibration check or on the opacity measurement.

During the test, two malfunctions occurred, which resulted in excessive instrument drift. The first malfunction took place when a plant electrostatic particulate collector developed a leak and enveloped the transmissometer in a cloud of particulates clogging the filters of the air purge system used for keeping the optical surfaces clean. The clogged filters reduced the flow of purge air and permitted the effluent to contaminate the transmissometer optical surfaces. This resulted in an increased drift of 5 and 3 percent opacity per week in the 0 and span, respectively. After the air filters were cleaned, the transmissometer was observed to continue to drift because of soiling of optical surfaces for the next 2 weeks. The 2 weeks of excessive drift following the air filter clogging were apparently due to contamination of the air tube following the filters. Normal drift performance returned after the tubes were cleaned.

The second malfunction of the instrument occurred during the last 3 weeks of operation and appeared as an erratic instrument 0 and span check which resulted in an apparent zero and span drift of 2.5 and 1.0 percent opacity drift per week, respectively. Examination of the instrument at the time of removal from the stack showed the erratic behavior of the 0 and span check to be due to a loose calibration reflector. It would be desirable to treat the reflector retaining screws and any critical hardware subject to displacement by vibration by some manner to keep them locked in place.

A study similar to the SO_2 work was conducted on NO_x monitoring systems at the Duke Power Plant in Charlotte. The same stack source and experimental facilities were used. The monitoring systems were operated for a period of about 3 months, September to November 1973. The monitoring systems included across-the-stack UV absorption, extractive NDIR and chemiluminescent techniques with permeation and water condensation interfaces, and extractive visible absorption techniques. Reference Method No. 7 was run concurrently and at various times during the 3-month period for a total of about 50 measurements. A range of particulate loading was encountered as in the case of the SO_2 study.

The objectives of this study were to compare the results of various analytical and sampling approaches to the measurement of NO_x and to evaluate and validate the applicability of the proposed specifications and test procedures for monitoring NO_x emissions from a coal-burning power plant.

Table D-1 summarizes some of the results on the NO_x monitoring system. The range of values for the test parameters is of the same order of magnitude for the NO_x monitors as those for the SO_2 monitors. The accuracy values for the NO_x monitors are based on a test procedure using sets of two Method 7 measurements. The test procedure requiring sets of three measurements should improve the accuracy values.

APPENDIX E.
EXAMPLE:
PERFORMANCE SPECIFICATIONS AND SPECIFICATION TEST PROCEDURES FOR MONITORS OF POLLUTANT GAS EMISSIONS FROM STATIONARY SOURCES

Performance specifications for continuous measurement systems for pollutant gases are given in terms of critical operating parameters. Test procedures are given to test the capability of the measurement systems to conform to the performance specifications.

1. Principle and Applicability

   1.1 Principle - Pollutant gases are sampled continuously in the stack emissions, and the gas concentration is analyzed continuously as a function of time. Sampling may include either the extractive or non-extractive (in-situ) approach.

   1.2 Applicability - The performance specifications are given for continuous pollutant gas measurement systems applied to specific source-pollutant combinations. The following discussion is addressed to SO_2 and NO_x emissions from coal-burning power plants. Instrument system should be capable of operation within performance specifications at particulate loadings and in a temperature range corresponding to those of the environment of the installation.

2. Apparatus

   2.1 Calibration Gas Mixture - Mixture of a known concentration of the pollutant gas in oxygen-free nitrogen.

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Nominal concentrations of 30 percent, 60 percent, and 90 percent of span are recommended. It is strongly recommended that the gas mixture be analyzed by a reference method prior to use.

2.2 Zero Gas - A gas containing no more than 1 ppm of the pollutant gas.

2.3 Equipment for measurement of pollutant gas concentration using the reference method.

2.4 Strip Chart Recorder - Analog strip chart recorder, input voltage range compatible with analyzer system output, full scale (per travel) in two seconds or less.

2.5 Continuous measurement system for pollutant gas.

3. Definitions

3.1 Measurement System - The total equipment required for the determination of a pollutant gas concentration in a given source effluent. The system consists of three major subsystems:

1. Sampling Interface - That portion of the measurement system that performs one or more of the following operations: delineation, acquisition, transportation, and conditioning of a sample of the source effluent or protection of the analyzer from the hostile aspects of the sample or source environment.
2. Analyzer - That portion of the system which senses the pollutant gas and generates a signal output that is a function of the pollutant concentration.

3. Data Presentation - That portion of the measurement system that provides a display of the output signal in terms of concentration units.

3.2 Span - The value of pollutant concentration at which the measurement system is set to produce the maximum data display output. For the purposes of this method, the span shall be set at a pollutant gas concentration of 1.5 times the emission standard or the pollutant gas concentration of interest.

3.3 Accuracy (Relative) - The degree of correctness with which the measurement system yields the value of gas concentration of a sample relative to the value given by a defined reference method. This accuracy is expressed in terms of error which is the difference between the paired concentration measurements. The error is expressed as a percentage of the reference mean value.

3.4 Calibration Error - The difference between the pollutant concentration indicated by the measurement system and the known concentration of the test gas mixture.

3.5 Zero Drift - The change in measurement system output over a stated period of time of normal continuous operation when the pollutant concentration at the time of the measurements is zero.

3.6 Calibration Drift - The change in measurement system output over a stated period of time of normal continuous operation when the pollutant concentration at

the time of the measurements is the same known upscale value.

3.7 Repeatability - A measure of the measurement system's ability to give the same output reading(s) upon repeated measurements of the same pollutant concentration(s).

3.8 Response Time - The time interval from a step change in pollutant concentration at the input to the measurement system to the time at which 95 percent of the corresponding final value is reached as display on the measurement system data presentation device.

3.9 Operational Period - A minimum period of time over which a measurement system is expected to operate within certain performance specifications without unscheduled maintenance, repair or adjustment.

4. Measurement System Performance Specifications

The following performance specifications shall be met in order that a measurement system shall be considered acceptable under this method.

Parameter	Specification
a. Accuracy (relative)	$\leq$ 20% of mean reference value
b. Calibration Error	$\leq$ 5% of each test gas value*
c. Zero Drift (2 hour)	$\leq$ 2% of emission standard*
d. Zero Drift (24 hour)	$\leq$ 4% of emission standard*

*Absolute mean value + percent confidence interval.

Parameter	Specification
e. Calibration Drift (2 hour)	≤ 2% of emission standard*
f. Calibration Drift (24 hour)	≤ 5% of emission standard*
g. Response Time	10 minutes (maximum)
h. Operational Period	168 hours

*Absolute mean value ± 95% confidence interval.

5. Specification Test Procedures

5.1 Calibration Error and Repeatability Test - Set up and calibrate the complete measurement system according to the manufacturer's written instructions. Record the readings of calibration gas concentrations of approximately 30, 60, and 90 percent of span. Make a series of five nonconsecutive readings at each concentration (Example: 30 percent, 90 percent, 60 percent 90 percent, 30 percent, 90 percent, 60 percent, etc.) Convert the measurement system output readings to ppm.

5.2 Field test for accuracy (relative), zero drift, calibration drift, and operation period.

5.2.1 Set up and operate the measurement system in accordance with the manufacturer's written instructions and drawings. Operate the system for an initial 168 hour conditioning period. During this period the system should measure the pollutant gas content of the effluent in a normal operational manner.

5.2.2 After completion of this conditioning period, the formal 168 hour performance and operation test period shall begin. The system shall be monitoring the source effluent at all times when not being zeroed, calibrated, or

backpurged. During this 168 hour test period, make a minimum of nine (9) pollutant gas concentration measurements using the reference method at intervals of not less than 1 hour. For SO_2, each of the nine tests shall consist of a Method 6 SO_2 concentration measurement, plus the instrumental measurement. For NO_x, each of the nine tests shall consist of a set of three Method 7 NO_x concentration measurements, plus the instrumental measurement. In each set of three Method 7 measurements, three samples should be taken concurrently or within a 3-minute interval. The sampling location for the reference method shall be as prescribed. The sampling location for the monitoring method shall be as close to the location of the reference method sampling point as conditions will permit to demonstrate the specified accuracy. The reference method data shall be compared with simultaneously collected monitoring data for calculation of accuracy. Before and after each reference method test, record the values given by both zero and calibration concentrations. Record the values given by zero and calibration concentrations at two hour intervals until 15 sets of data are obtained. This two-hour period need not be consecutive but may not overlap. Zero and calibration corrections and adjustments are allowed only at 24 hour intervals or at such shorter intervals as the manufacturer's written instructions specify. Automatic corrections made by the measurement system without operator intervention or

initiation are allowable at any time. During the entire test period, record the values given by zero and calibration pollutant gas concentrations before and after adjustment at 24 hour intervals. Calibration checks are made with one test gas concentration between 70 and 90 percent of span.

5.3 Field Test for Reponse Time

5.3.1 This test shall be accomplished using the entire measurement system as installed including sample transport lines if used. Flow rates, line diameters, pumping rates, pressures, etc., shall be at the nominal values for normal operation as specified in the manufacturer's written instructions. In the case of cyclic analyzers, the response time test shall include one cycle. This test shall be repeated for each sampling point of multi-sampling point systems.

5.3.2 Introduce a zero concentration of pollutant gas into the measurement system sampling interface or as close to the sampling interface as possible. When the system output reading has stabilized, switch quickly to a known concentration pollutant gas at 70 to 90 percent of span. Record the time from concentration switching to final stable response. After the system response has stabilized at the upper level, switch quickly to a zero concentration of pollutant gas. Record the time from concentration switching to

final stable response; perform this test sequence three (3) times. The strip chart recorder charts or copies of them from this test should be included in the data submission with time scales and up and down scale values clearly marked.

6. Calculation, Data Analysis and Reporting

6.1 Procedure for Determination of Mean Values and Confidence Intervals

6.1.1 The mean value of a data set is calculated according to equation E-1.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

Equation E-1

where x_i = individual values

$\sum x_i$ = sum of the individual values

$\bar{x}$ = mean value

n = number of data points

6.1.2 The 95% confidence interval (two-sided) is calculated according to equation E-2.

$$C.I._{95} = \frac{t_{1-\alpha/2}}{\sqrt{n}} \sqrt{\frac{n(\sum x_i^2) - (\sum x_i)^2}{n(n-1)}}$$

Equation E-2

where $\sum x_i$ = sum of all data points

$\sqrt{n}$ = square root of the number of data points

$t_{1-\alpha/2} = t_{.975}$ for n samples from a table of percentages of the t distribution.

$C.I._{95}$ = 95% confidence interval estimate of the average mean value.

Typical Values for $t_{1-\alpha/2}$

n	$t_{.975}$	n	$t_{.975}$	n	$t_{.975}$
2	12.706	7	2.447	12	2.201
3	4.303	8	2.365	13	2.179
4	3.182	9	2.306	14	2.160
5	2.776	10	2.262	15	2.145
6	2.571	11	2.228	16	2.131

The values in this table are already corrected for n-1 degrees of freedom.

Use n equal to the number of samples as data points.

6.2 Data Analysis and Reporting

6.2.1 Accuracy (relative) - This calculation uses the reference method test data and the measurement system concentrations recorded at the times the reference method tests were run. Subtract the reference method test concentration from the measurement system concentration.* Repeat for all nine test pairs. Using this data, compute the mean difference and the 95% confidence interval using Equations E-1 and E-2. Report the sum of the absolute mean value and the 95% confidence interval as a percentage of the mean reference value.

6.2.2 Calibration Error - Using the data from Section 5.1 subtract the known value from the value shown by the measurement system for each of the 5 readings at each span test concentration. Calculate the mean of these differences values and the 95% confidence interval according to Equations E-1 and E-2. Report the sum of the absolute mean value and the 95% confidence interval as a percentage of test gas concentration.

*For SO_2, subtract the Method 6 values from the corresponding instrumental value. For NO_x, subtract the mean value of the set of three Method 7 values from the corresponding instrumental values.

6.2.3 Zero Drift (2 Hour) - Using the zero concentration values measured during the field test, calculate the mean value and the confidence interval using Equations E-1 and E-2. Report the sum of the absolute mean value and the confidence interval as a percentage of the emission standard.

6.2.4 Zero Drift - (24 Hour) - Using the zero concentration values measured every 24 hours during the field test, calculate the differences between the zero point after zero adjustment and the zero value 24 hours later just prior to zero adjustment. Calibrate the mean value of these points and the confidence interval using Equations E-1 and E-2. Report the sum of the absolute mean value and confidence interval as a percentage of the emission standard.

6.2.5 Calibration Drift (2 Hour) - Using the calibration values obtained at two-hour intervals during the field test, calculate the differences between the readings and the test gas value. These values should be corrected for the corresponding zero drift during that two-hour period. Calculate the mean and confidence interval of these corrected values using Equations E-1 and E-2. Report the sum of the absolute mean value and confidence interval as a percentage of the emission standard.

6.2.6 Calibration Drift (24 Hour) - Using the calibration values measured every 24 hours during the field test, calculate the differences between the calibration concentration reading after zero and calibration adjustment and the calibration

concentration reading 24 hours later after zero adjustment but before calibration adjustment. Calculate the mean value of these differences and the confidence interval using Equations E-1 and E-2. Report sum of the absolute mean value and confidence interval as a percentage of the emission standard.

6.2.7 Response Time - Using the charts from Section 5.3 calculate the time interval from concentration switching to 95% of the final stable value for all up scale and down scale tests. Report the mean of the three up scale test times and the mean of the three down scale test times. The two average times should not differ by more than 15% of the slower time. Report the slower time as the system response time.

6.2.8 Operational Period - During the 168 hour performance and operational test period, the measurement system shall not require any corrective maintenance or repair or replacement or adjustment other than that clearly specified as required in the operation and maintenance manuals as routine and expected during a one-week period. If the measurement system operates within the specified performance parameters and does not require corrective maintenance, repair, replacement or adjustment other than specified above, during the 168 hour test period, the operational period test will be successfully concluded. Failure of the measurement to meet this requirement shall call for repetition of the 168 hour test period. Portions of the test which were satisfactorily completed need not be repeated. Failure to meet any performance specifications shall call for a repetition of the one

week performance test period and that portion of the testing which is related to the failed specification. All maintenance and adjustments required shall be recorded. Output readings shall be recorded before and after all adjustments.

7. Supplemental References
   Experimental Statistics, National Bureau of Standards, Handbook 91, 1963, P. 3-31, Paragraph 3-3.1.4.

APPENDIX F.
EXAMPLE:*
PERFORMANCE SPECIFICATIONS AND SPECIFICATION TEST PROCEDURES FOR TRANSMISSOMETER SYSTEMS FOR CONTINUOUS MEASUREMENT OF THE OPACITY OF STACK EFFLUENTS

Specifications for continuous measurement of visible emissions by transmissometry are given in terms of critical design, performance, and installation parameters. Test procedures are given to test the capability of the systems to conform to the performance specifications.

1. Principle and Applicability

1.1 Principle. Transmissometry is a direct measurement of attenuation of visible radiation (opacity) by particulates in a stack effluent. Light from a lamp is projected across the stack of a pollution source to a light sensor. The light is attenuated due to absorption and scatter by the particulates in the effluent. The percentage of light attenuated is defined as the opacity of the emission. A clean stack that does not attenuate light will have a transmittance of 100 or an opacity of 0. An opaque stack that attenuates all of the light will have a transmittance of 0 or an opacity of 100 percent.

1.2 Applicability. The performance specifications are given for transmissometer systems for continuous measurement of the opacity of aerosol within the effluent (in-situ) of a pollution source. The method is applicable to the measurement of the opacity of the

*For coal-burning power plant.

effluent at points in the plume at the stack exit remote from the measurement point provided the characteristics of the aerosols in the effluent are maintained between the measurement point and the remote point of interest in the plume. Water in condensed form is an interference to the measurement.

2. Apparatus

2.1 Neutral Density Filters. Filters with neutral spectral characteristics and known optical densities to visible light. Filters 5- or 6-inch square or 6-inch diameter with nominal optical densities of 0.1, 0.2, and 0.3 (20, 37, and 50 percent opacity) are required. Although calibrated filters with accuracies reported to within 3 percent are available, it is recommended that filter calibrations be checked with a well-collimated photopic transmissometer of known linearity prior to use.

2.2 Strip Chart Recorder. Analog strip chart recorder with input voltage range and performance characteristics compatible with the measurement system output.

2.3 Opacity Measurement System. An in-stack transmissometer (folded or single path) with the optical design specifications designated below, associated control units and apparatus to keep optical surfaces clean.

3. Definitions

3.1 Measurement System. The total equipment required for the continuous determination of a pollutant concentration in a source effluent. The system consists of three major subsystems:

3.1.1 Sampling Interface - That portion of the measurement system that performs one or more of the following operations: delineation, acquisition, transportation, and conditioning of a sample of the source effluent, or protection of the analyzer from the effluent.

3.1.2 Analyzer - That portion of the system which senses the pollutant gas and generates a signal output that is a function of the pollutant concentration.

3.1.3 Signal Processor - That portion of the measurement system that processes the analyzer output and provides a display of the output signal in terms of pollutant concentration.

3.2 Span. The value of pollutant concentration at which the measurement is set to produce the maximum data display output. For the purpose of this method, the span shall be set at an opacity of 50 percent for an effluent depth equal to the stack exit diameter of the source.

3.3 Calibration Error. The difference between the pollutant concentration indicated by the measurement system and the known values of a series of test standards. For this method the test standards are a series of calibrated neutral density filters.

3.4 Zero Drift. The change in measurement system output over a stated period of time of normal continuous operation when the pollutant concentration at the time of the measurements is zero.

3.5 Calibration Drift. The change in measurement system output over a stated period of time of normal continuous operation when the pollutant concentration at the time of the measurements is the same known up scale value.

3.6 Repeatability. A measure of the measurement system's ability to give the same output reading(s) upon repeated measurements of the same pollutant concentration(s).

3.7 Response Time. The time interval from a step change in pollutant concentration in the stack of the source at the input to the measurement system to the time at which 95 percent of the corresponding final value is reached as displayed on the measurement system data presentation device.

3.8 Operational Period. A minimum period of time over which a measurement system is expected to operate within certain performance specifications without unscheduled maintenance, repair, or adjustment.

3.9 Transmittance. The fraction of incident light that is transmitted through an optical medium of interest.

3.10 Opacity. The fraction of incident light that is attenuated by an optical medium of interest. Opacity (O) and transmittance (T) are related as follows:

$$O = 1 - T$$

3.11 Optical Density. A logarithmic measure of the amount of light that is attenuated by an optical medium of interest. Optical density (D) is related to the transmittance and opacity as follows:

$$D = -\log_{10} T$$

$$D = -\log_{10} (1-O)$$

3.12 Spectral Response. The relative response of a transmissometer to radiation of different wavelengths.

3.13 Angle of View. The maximum (total) angle of radiation that is

seen by the photo-detector assembly of an optical transmissometer.

3.14 Angle of Projection. The maximum (total) angle of radiation that is projected by the lamp assembly of an optical transmissometer.

3.15 Pathlength. The depth of effluent in the light beam between the receiver and the transmitter of the single pass transmissometer, or the depth of effluent between the transceiver and reflector of a double pass transmissometer.

4. Installation Specifications

4.1 Location. The transmissometer must be located across a section of duct or stack that will provide a particulate flow through the optical volume of the transmissometer that is representative of the particulate flow through the duct or stack.

4.1.1 The transmissometer location shall be downstream from all particulate control equipment.

4.1.2 The transmissometer location shall be located as far from bends and obstructions as practical.

4.1.3 The transmissometer that is located in the duct or stack following a bend shall be installed in the plane of the bend where possible.

4.1.4 The transmissometer should be installed in the most accessible location possible.

4.1.5 The transmissometer location in a section of duct or stack where a representative particulate concentration is in doubt shall provide an average measure of the opacity of the effluent in the duct or stack. The location shall be determined by examining the opacity profile of the effluent at a series of positions across the duct or stack while the plant is operating

at full load.

4.2 Slotted Tube. Installations that require the use of a slotted tube shall use a slotted tube of sufficient size and blackness so as not to interfere with the free flow of effluent through the entire optical volume of the transmissometer or reflect light into the light detector of the transmissometer.

4.3 Pathlength. It is recommended that the pathlength or depth of effluent for the transmissometer include the entire width or diameter of the duct or stack. Installations using a shorter pathlength must use extra caution in determining the measurement location representative of the particulate flow through the duct or stack.

4.4 Recorder Output. The transmissometer output shall permit expanded display of the in-stack opacity on a standard 0 to 100 percent scale. In addition, a graph shall be provided with the installation to show the relation between the standard 0 to 100 percent readout scale and the opacity of the effluent for a pathlength equal to the stack exit diameter.

The relation for constructing the graph is:

$$\log(1 - O_1) = (l_1/l_2) \log(1 - O_2)$$

where l_1 is the stack exit diameter and O_1 is the opacity of the effluent at the stack exit diameter, l_2 is the in-stack pathlength of the transmissometer, and O_2 is the measured opacity of the effluent within the transmissometer path.

The opacity standard is based on the opacity of the effluent

at the stack exit diameter.

5. Optical Design Specifications

The following optical design specifications shall be met in order that a measurement system shall be considered acceptable under this method:

PARAMETER	SPECIFICATION
a. Spectral response	Peak and mean response within 500 to 600 nm, less that 10% of peak response outside 400 to 700 nm.
b. Angle of view	5 degrees maximum (total angle)
c. Angle of projection	5 degrees maximum (total angle)

6. Design Specification Data and Test Procedures

6.1 Spectral Response. Obtain spectral data for detector, lamp, and filter components used in the transmissometer from their respective manufacturers.

6.2 Angle of View. Set the receiver up as specified by the manufacturer. Draw an arc with radius of 3 meters. Measure the receiver response to a small (less than 3 centimeters) non-directional light source at 5-centimeter intervals on the arc for 26 centimeters on either side of the detector centerline. Repeat the test in the vertical direction.

6.3 Angle of Projection. Set the projector up as specified by the manufacturer. Draw an arc with radius of 3 meters. Using

a small photoelectric light detector (less than 3 centimeters), measure the light intensity at 5-centimeter intervals on the arc for 26 centimeters on either side of the light source centerline of projection. Repeat the test in the vertical direction.

7. Measurement System Performance Specifications

The following performance specifications shall be met in order that a measurement system shall be considered acceptable under this method.

PARAMETER	SPECIFICATIONS
a. Calibration Error	≤10% of test filter value*
b. Zero Drift (24 hr)	≤10% of emission standard*
c. Calibration Drift (24 hr)	≤10% of emission standard*
d. Response Time	10 seconds (maximum)
e. Operational Period	168 hr

*Absolute mean value + 95 percent confidence interval.

8. Performance Specification Test Procedures

8.1 Laboratory Test for Calibration Error, Repeatability, and Response Time:

8.1.1 Set up and calibrate the measurement system as specified by the manufacturer's written instructions using a 3-meter pathlength. Span the instrument for 0 to 50 percent opacity. Insert a

range of neutral density filter standards in the transmissometer path at the 2.5-meter point. A minimum of three neutral density filters with nominal opacities of 20, 37, and 50 percent calibrated within 3 percent must be used. Make a total of five non-consecutive readings for each filter. Record the measurement system output readings in percent opacity.

8.1.2 Insert the 50 percent filter in the transmissometer path five times and record the time required for the system to respond to 95 percent of final zero and span values.

8.2 Field Test for Zero Drift, Calibration Drift, and Operational Period.

8.2.1 Set up and operate the measurement system in accordance with the manufacturer's written instructions and drawings. Operate the system for an initial 168 hour conditioning period. During this period the system should measure the opacity of the effluent in a normal operational manner.

8.2.2 After completion of this conditioning period, the formal 168-hour operational test period shall begin. The system shall be monitoring the source effluent at all times when not being zeroed or calibrated. At 24-hour intervals over the specified operational period, the zero and span of the measurement system shall be checked according to the manufacturer's written instructions. The span value shall not be less than 1.5 times the emission standard. After the zero and span check, clean all optical surfaces open to the effluent, re-align optics and make any necessary adjustments to the calibration of the system. Zero and calibration corrections and adjustments are allowed only at 24-hour intervals or at such shorter intervals as manufacturer's written instructions specify. Automatic corrections made by the

measurement system without operator intervention are allowable at any time. During the entire test period, record the values of zero and span opacities before and after cleaning, aligning, and adjusting the system at 24-hour intervals.

9. Calculation, Data Analysis, and Reporting

9.1 Procedure for Determination of Mean Values and Confidence Intervals.

9.1.1 The mean value of data set is calculated according to equation F-1.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad \text{Equation F-1}$$

where x_i = individual values $\sum$ = sum of the individual values

$\bar{x}$ = mean value

n = number of data points

9.1.2 The 95 percent confidence interval (two-sided) is calculated according to equation F-2.

$$C.I._{95} = \frac{t_{1-\alpha/2}}{\sqrt{n}} \sqrt{\frac{n(\Sigma X_i^2) - (\Sigma X_i)^2}{n\,(n-1)}} \qquad \text{Equation F-2}$$

where ΣX_i = sum of all data points

$\sqrt{n}$ = square root of the number of data points

$t_{1-\alpha/2} = t_{.975}$ for n samples from a table of percentages of the t distribution

TABLE OF TYPICAL VALUES FOR $t_{1-\alpha/2}$

n	$t_{.975}$	n	$t_{.975}$	n	$t_{.975}$
2	12.706	7	2.447	12	2.201
3	4.303	8	2.365	13	2.179
4	3.182	9	2.306	14	2.160
5	2.776	10	2.262	15	2.145
6	2.571	11	2.228	16	2.131

The values in this table are already corrected for n-1 degrees of freedom. Use n equal to the number of samples as data points.

9.2 Data Analysis and Reporting

9.2.1 Spectral Response. Combine the spectral data obtained in accordance with Section 6.1 to determine the effective spectral response of the transmissometer. Report effective wavelength response curve and mean response of the transmissometer.

9.2.2 Angle of View. Using the data obtained in accordance with Section 6.2, calculate the response of the receiver as a function of viewing angle in the horizontal and vertical directions (26 centimeters of arc with a radius of 3 meters equal 5 degrees). Report relative angle of view curves.

9.2.3 Angle of Projection. Using the data obtained in accordance with Section 6.3, calculate the response of the photoelectric

detector as a function of projection angle in the horizontal and vertical directions. Report relative angle of projection curves.

9.2.4 Calibration Error. Using the data from Section 8.1 subtract the known filter opacity value from the value shown by the measurement system for each of the 15 readings. Calculate the mean of the five difference values at each test filter value and the 95 percent confidence interval according to Equations F-1 and F-2. Report the sum of the absolute mean value and the 95 percent confidence interval as a percentage of the test filter value.

9.2.5 Zero Drift. Using the zero concentration values measured every 24 hours during the field test (Section 8.2), calculate the differences between the zero point after cleaning, aligning, and adjustment, and the zero value 24 hours later just prior to cleaning, aligning and adjustment. Calculate the mean value of these points and the confidence interval using Equations F-1 and F-2. Report the sum of the absolute mean value and the 95 percent confidence interval as a percentage of the emission standard.

9.2.6 Calibration Drift. Using the span value measured every 24 hours during the field test, calculate the differences between the span value after cleaning, aligning, and adjustment of 0 and span, and the span value 24 hours later just after cleaning, aligning, and adjustment of 0

and before adjustment of span. Calculate the mean value of these points and the confidence interval using Equations F-1 and F-2. Report the sum of the absolute mean value and the confidence interval as a percentage of the emission standard.

9.2.7 Response Time. Using the data from Section 8.1 calculate the time interval from filter insertion to 95 percent of the final stable value for all up scale and down scale traverses. Report the mean of the 10 up scale and down scale test times.

9.2.8 Operational Period. During the 168 hour performance and operational test period, the measurement system shall not require any corrective maintenance or repair or replacement or adjustment other than that clearly specified as required in the operation and maintenance manuals as routine and expected during a one-week period. If the measurement system operated within the specified performance parameters and did not require corrective maintenance, repair, replacement, or adjustment other than specified above, during the 168 hour test period, the operational period test will be successfully concluded. Failure of the measurement to meet this requirement shall call for a repetition of the 168 hour test period. Portions of the test which were satisfactorily completed need not be repeated. Failure to meet any performance specifications shall call for a repetition of

the one-week performance test period and that portion of the testing which is related to the failed specification. All maintenance and adjustments required shall be recorded. Output readings shall be recorded before and after all adjustments.